Effects of Small-Scale Bathymetric Roughness on the Global Internal Wave Field

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LONG-TERM GOALS

The small-scale roughness properties of the seafloor are increasingly being recognized as critical parameters in determining important processes in physical oceanography. For instance, *in situ* observations (e.g., Polzin et al., 1997) find that mixing levels are greatly elevated in regions of rough topography. Gille et al. (2000) demonstrate that mesoscale eddy energy tends to be lower in areas where the bottom is rough (suggesting the possibility that dissipation of eddy energy takes place in such areas), and Egbert and Ray (2003) show that substantial tidal dissipation occurs in such areas. The dissipation is generally thought to arise from the breaking of internal waves generated by flows over the rough seafloor. On the time scales of internal waves, mesoscale eddies and the general circulation can be regarded as steady, while tides are oscillatory. The physics of linear internal wave generation is different for these two classes of motions (e.g., Bell 1975), but for both types of flows the wave generation is strongly dependent on the horizontal and vertical scales inherent in the bottom topography. Using the classical formulation for lee waves (e.g., Cushman-Roisin, 1994, St. Laurent, 1999), one can argue that horizontal wavelengths ranging from ~60 m to 6 km generate internal waves when forced by steady flows. Features typical of abyssal hill morphology (e.g., 50 m height over 1 km horizontal scale) will generate a significant vertical internal wave energy flux. High-resolution regional models (e.g., Zilberman and Merrifield, 2006) demonstrate that topographic information on scales of order 3 km are also important for internal tides. Non-linear effects may be important as well, as some oceanographers (e.g., Thurnherr and Richards, 2001; Thurnherr et al., 2002; Thurnherr and Speer, 2003; St. Laurent and Thurherr, 2007) have argued from observational data that turbulence associated with hydraulic jumps occurs in area of rough topography when the Froude number exceeds an order one threshold. This occurs when topography over scales of 1 km exceeds 20 m in height, which is typically the case for abyssal hill morphology.

A significant dilemma for physical oceanographers studying these processes is that the kind of bathymetric resolution required to model these processes over entire ocean basins are not available, nor will be any time soon. Acoustic bathymetric data, which can achieve lateral resolutions of 0.1-0.2 km, presently cover only a few percent of the ocean floor beyond the exclusive economic zones in coastal areas. A complete swath survey of all the deep oceans would take ~200 years of ship time at a cost of billions of dollars (Carron et al., 2001). The most comprehensive determination of bathymetry world-wide is the Smith and Sandwell (1994; 1997; 2004) model derived from satellite altimetry data combined with data from ship soundings, but the resolution of this product is limited to >10 km in the deep ocean. We seek to resolve this dilemma through a novel approach of relating the texture of

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14. ABSTRACT
The small-scale roughness properties of the seafloor are increasingly being recognized as critical parameters in determining important processes in physical oceanography. For instance, in situ observations (e.g., Polzin et al., 1997) find that mixing levels are greatly elevated in regions of rough topography. Gille et al. (2000) demonstrate that mesoscale eddy energy tends to be lower in areas where the bottom is rough (suggesting the possibility that dissipation of eddy energy takes place in such areas), and Egbert and Ray (2003) show that substantial tidal dissipation occurs in such areas. The dissipation is generally thought to arise from the breaking of internal waves generated by flows over the rough seafloor.

15. SUBJECT TERMS

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satellite altimeter data to seafloor roughness characteristics. We will then address issues of importance to the Navy with tide models that utilize this information, either by directly resolving internal wave generation over the rough seafloor, or by parameterizing the dissipation of these internal waves. In particular, we will investigate internal wave generation in a global baroclinic tide model, and we will investigate the effect of parameterized dissipation over rough topography in both barotropic and baroclinic global tide models.

OBJECTIVES

Our main objectives are to characterize seafloor roughness from satellite altimetry data and investigate the impact of rough topography on the global internal tide field. Specific tasks are:

(1) Full spectral characterization of altimeter noise world-wide and transfer function for predicting resultant noise in the gravity signal via the processing path.

(2) Advance the study of the relationship between gravity and abyssal hill fabric.

(3) Generate map of abyssal hill roughness parameters across the ocean basins.

(4) Determine the location of dissipation in global baroclinic tide models.

(5) Parameterize unresolved topographic wave drag in global tide models.

(6) Determine the impact of better roughness estimates on the resolved generation of internal tides in a global model.

APPROACH

Satellite altimetry data and the derived gravitational field (Fig. 1) may make it possible to infer seafloor statistical parameters over entire ocean basins, and are the focus of tasks 1-3 noted above. While it is difficult, owing to the limits of upward continuation of gravity in the deep ocean, for seafloor features < ~10 km scale to be distinguished individually in the altimetry data, the aggregate fabric of small-scale features, such as abyssal hill morphology, can have a quantifiable effect on the gravity fabric (Goff and Smith, 2003; Goff et al., 2004). Our governing hypothesis, which is partially confirmed by these prior results, is that an empirical transfer function can be determined which relates the primary attributes of bathymetric and gravity roughness (rms height, characteristic horizontal scales, and fabric orientation) to each other. However, at these limiting scales of altimetry resolution, process filtering (Smith and Sandwell, 1997), which is necessary to convert raw altimetry data into coherent gravity field estimates, and data noise, related both to data uncertainties and oceanographic variability, will also have a significant effect on gravity fabric. These must be fully accounted for.

The Goff and Smith (2003) and Goff (2004) analyses demonstrate clearly the importance of quantifying altimetry noise (Task 1 above) if we are to extract abyssal hill roughness properties from the altimetry data set. Altimetric noise is neither constant nor simple in statistical character. To characterize noise in the gravity map, we must first characterize noise in the raw altimetry data, prior to the application of the various filtering and processing steps. In our analyses, we have devised a means of largely isolating the noise by differencing nearest-neighbor tracks to remove most static components of the field, and high-pass filtering to remove larger-scale variations associated with mesoscale oceanographic circulation. We employ a covariance analysis to quantify the residual profiles, which are dominated by noise processes. As demonstrated in last year's progress report, we were able to decompose the noise into uncorrelated and correlated components, the measures of which are closely

correlated with identifiable environmental variables, such as significant wave heights, rainfall rates, sea ice distribution, and the subtropical jet stream. Sea surface height noise statistical parameters have been estimated world-wide for both Geosat and ERS1 geodetic missions. The next step in our approach is to synthesize the noise process along all the tracks for both missions, and then to run these synthetic data through the full processing steps for estimating the global gravity field. This will provide us with a global estimate of gravity noise characteristics, which will, in turn, enable us to confidently ascertain the component of gravity roughness that can be associated with abyssal hill roughness.

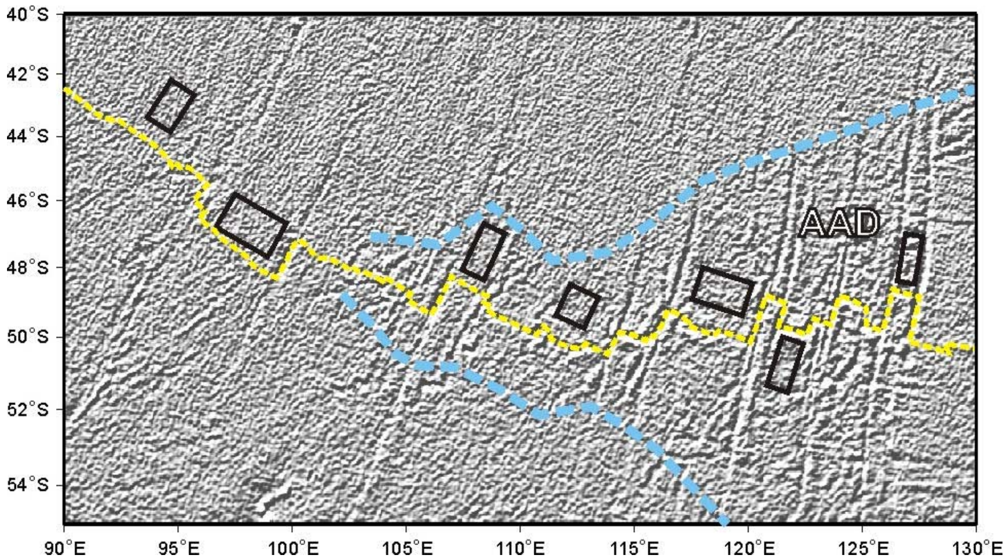

Figure 1. Sun-shaded altimetric gravity field (Sandwell and Smith, 1997), emphasizing roughness, over a portion of the Southeast Indian Ridge (yellow) corresponding to a change in ridge morphology: from an axial high in the west to an axial valley in the east progressing into the Australian-Antarctic Discordance (AAD), and a corresponding change in abyssal hill roughness (Goff et al., 1997). The blue dashed line marks a visually-determined textural boundary off axis. Boxes indicate areas chosen by Goff and Smith (2003) for gravity texture estimation, which demonstrated that the quantitative characterization of gravity texture varied in concert with the abyssal hill roughness.

The approach described above for obtaining abyssal hill roughness parameters from altimetric gravity roughness is a time-intensive, multi-year project. In the short term, we need to provide an interim product under Task 3: a realistic rendering of abyssal hill roughness to provide input for the ocean modeling parts of our objectives (Tasks 4-6, which are detailed below). To provide this information, we generate a prediction of abyssal hill roughness statistical parameters world-wide via relationships presented by (1) Goff et al. (1997) for the average statistical properties of abyssal hills as a function of spreading rate (Figure 2) and direction (Figure 3), and (2) by Webb and Jordan (2001) for the modification to these roughness parameters as a function of sediment thickness (Figure 4). These relationships are constrained by digital maps of paleo-spreading rate and direction (Meuller et al. 2008), and sediment thickness (Divens, NGDC webs site). Next, modifying synthetic abyssal hill topography code presented by Goff and Jordan (1998) to work with variable strike input, we have generated synthetic abyssal hill roughness globally on 1-minute and 30-second grids.

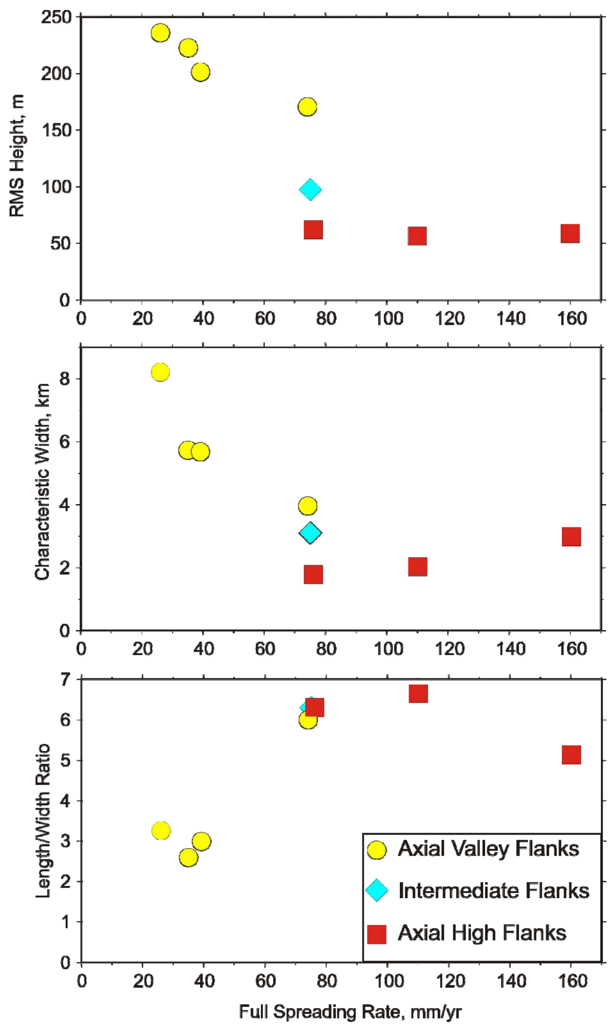

Figure 2. Average abyssal hill properties as a function of spreading rate (Goff et al., 1997).

The spatial distribution of dissipation in the ocean is a matter of intense interest in the oceanographic community, including the Navy. Much of the interest stems from the suggestion by Munk and Wunsch (1998) that the strength of the meridional overturning circulation is controlled by ocean mixing. In addition, the general oceanic circulation in models (e.g., Scott and Marotzke 2002) shows a strong sensitivity to the spatial distribution (in both the vertical and horizontal directions) of mixing. Mixing diffusivity κ is related to energy dissipation ε by the relation $\kappa = \Gamma\varepsilon/N^2$, where Γ is an efficiency factor of about 0.2 and N is the Brunt-Vaisala buoyancy frequency (Osborn 1980). Since mixing is connected to dissipation, quantification of mixing in the ocean must consider energy sinks, which balance energy sources in averages taken globally and over long periods of time. Quantification of the sources and sinks of energy for the deep ocean has been studied in earnest in recent years. Wunsch (1998) showed that the winds put approximately 1 TW of energy into the oceanic general circulation, while Alford (2001) showed that winds put about 0.5 TW of energy into the near-inertial internal wave field. The details of how these wind energy inputs are eventually converted into a dissipation are not yet well known. Tides put a total of 3.5 TW into the ocean, and of this about 2.5 TW is dissipated in coastal areas, where tidal velocities are much larger, while 1 TW is dissipated in the open ocean, in regions of rough topography (Egbert and Ray 2003). Although the budget for tidal energy is understood better than for wind-forced motions, important questions about the tidal energy cycle remain.

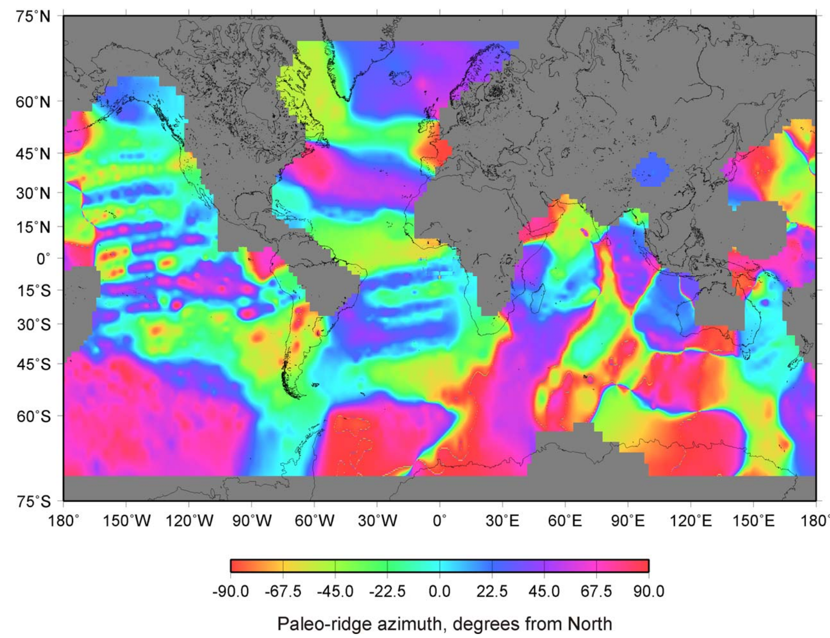

Figure 3. Paleo-ridge azimuths (D. Mueller, personal communiction) for predicting abyssal hill orientations.

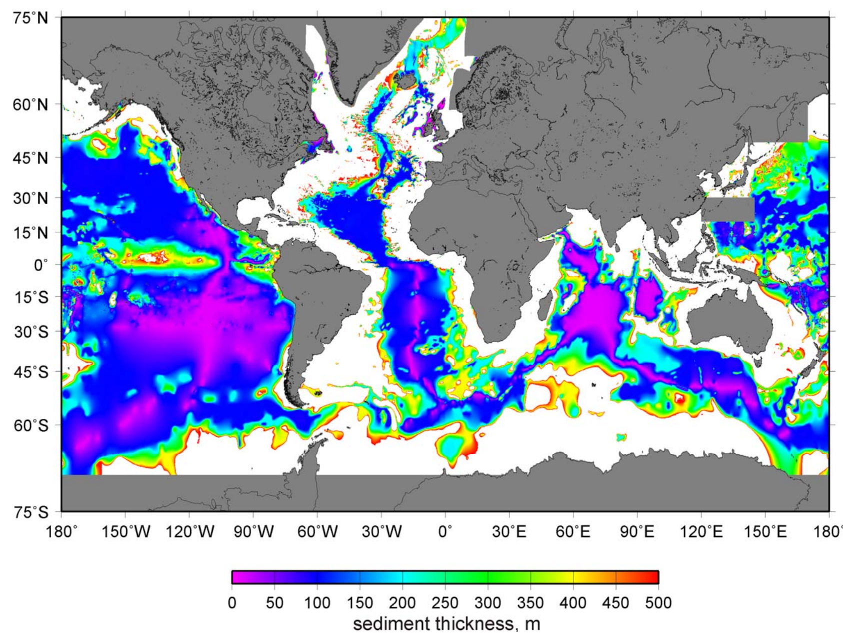

Figure 4. Global sediment thickness distribution (Divens, NGDC webs site) for predicting modification to abyssal hill roughness via Webb and Jordan (2001) formulations

In task 4 we will use the global baroclinic tide model of Arbic et al. (2004) to examine whether the dissipation of internal tides generated in the open ocean takes place in coastal areas, in the abyssal parts of the open ocean, or in the thermocline of the open ocean. In tasks 5 and 6 we will use the roughness estimates from our work on tasks 1 to 3 in global tide models. In task 5 we will examine the

difference that a better roughness estimate makes on our parameterizations of unresolved topographic wave drag, which are used in both barotropic and baroclinic tide models. In task 6 we will return to global model of the resolved internal tide field, as in task 4, but this time with better estimates of seafloor roughness, which will improve the resolution of high baroclinic modes.

The new bathymetry for the Global Tidal Model (HYCOM) is to be derived by combining the latest Smith and Sandwell (1997) bathymetric database (SS) together with an empirically derived estimate of abyssal hill roughness as described above. Both products are provided at a resolution of 30 arc seconds. The SS data has been interpolated onto a 1/12.5 degree HYCOM grid using a radial Blackman filter. The SS bathymetry also includes a parameter (SID) to identify the source of actual sounding data used in the preparation of the bathymetric data. We convert this parameter to a field of 0 and 1 to indicate that the bathymetry is measured (SID = 1) or estimated from altimetry (SID = 0). The Goff roughness prediction (G) is an empirically derived estimate of bottom roughness for the worlds oceans. If the SS data is derived from actual soundings then we do not wish to alter the bathymetry by adding a roughness parameter. Therefore, in order to add the Goff roughness parameter which resolves abyssal hill roughness of order 2-10 km, we calculate a weight alpha(x,y) for each ordinate pair on the 30 arc second grid. alpha is calculated in the same manner as the HYCOM model bathymetry but with a filter radius R = 5 km and 10 km. We produce a new bathymetry h_SS_G(x'y') on a 30 arc second grid using:

$$h\_SS\_G(x',y') = SS(x',y') + (1 - alpha) * G(x',y'),$$

WORK COMPLETED

Goff as completed analysis of both Geosat and ERS1 altimetry data to provide a world-wide analysis of altimetry noise at scales < 50 km (i.e., scales that are of importance to characterizing abyssal hill fabric). Some of these results were detailed in the previous progress report and will not be repeated here. That work is the topic of a manuscript in preparation. Goff has since generated a synthetic noise data set for all the Geosat and ERS1 track lines. These profiles are awaiting full altimetry processing by collaborators Walter Smith and David Sandwell for eventual estimation of altimetric gravity noise characteristics. More significantly, Goff has formulated a preliminary world-wide, synthetic abyssal hill roughness grid from predictions based on average abyssal hill characteristics as a function of spreading rate and direction, as well as modifications by sediment cover. These grids are now being used by Arbic for tide modeling, and initial results from that work are expected soon.

Patrick Timko, a postdoc, has been working full-time on this project since May 2008. We expect that in the near-future he will switch over to working half-time on this project, and half-time on the NRL contract. For the ONR roughness project, Patrick has learned how to run and analyze high-resolution HYCOM tide runs, and is nearly finished constructing bathymetries as described above. We plan in the very near future to run two-layer versions of HYCOM on both the SS and SS+Goff grids. Once we get the two-layer model working on both bathymetries, we plan to get a multi-layer model (say, for instance, a 15-layer model) working on both bathymetries. We will look for increased internal wave activity in the runs on the SS+Goff bathymetry due to the increased roughness. We expect that the multi-layer runs will exhibit more sensitivity to the extra roughness, because higher vertical resolution implies the presence of higher vertical modes, which are more sensitive than low modes to small scales in the bathymetry. After we do the runs described above we also plan to run at higher resolution (1/25th degree). We expect at that resolution the goff roughness will have a more pronounced effect.

RESULTS

A global predictions of abyssal hill statistical characteristics has been completed using the approach outlined above. Here we display plots of rms heights (Figure 5), width scale parameter (Figure 6), and length scale parameters (Figure 7). Scale parameters, which define the functional form of the autocovariance function, are proportional to the inverse of the charactistic width or length. From these predictions we have generated global synthetic realizations of abyssal hill-scale roughness at both 1-minute and 30-second resolution. The North Atlantic sector of the 1-minute grid is shown in Figure 8.

IMPACT/APPLICATIONS

Synthetic, predictive maps of mall-scale seafloor roughness can be used to realistically "roughen" lower-resolution global bathymetry maps, which can then be incorporated into oceanographic modeling efforts to predict critical phenomena such as the generation of internal waves and mixing by both tidal and non-tidal (i.e., mesoscale eddy) flows.

RELATED PROJECTS

Arbic has a separate contract with the Stennis branch of the Naval Research Laboratory to implement global tides in HYCOM. HYCOM is planned to be the next-generation Navy operational global model. Arbic has developed a good working relationship with several of the key HYCOM investigators (e.g. Alan Wallcraft, Joe Metzger, Harley Hurlbert, Jim Richman, and others). Wallcraft and Arbic implemented tides into HYCOM, and Wallcraft and Metzger recently completed a 5-year run of the global 1/12 degree model with tides. Preliminary results already indicate important impacts of the tides on the ocean general circulation, and several analyses and further improvements to the model are planned. The parameterization of topographic wave drag on both tidal and non-tidal motions in HYCOM is expected to be enhanced by the bathymetric roughness work done in the current project. In addition, postdoc Patrick Timko, working with Arbic, has learned to run and analyze HYCOM tidal simulations, as well as to constuct bathymetric grids for use in HYCOM. Timko plans to continue to work on both Navy-funded projects, thus benefitting both projects greatly.

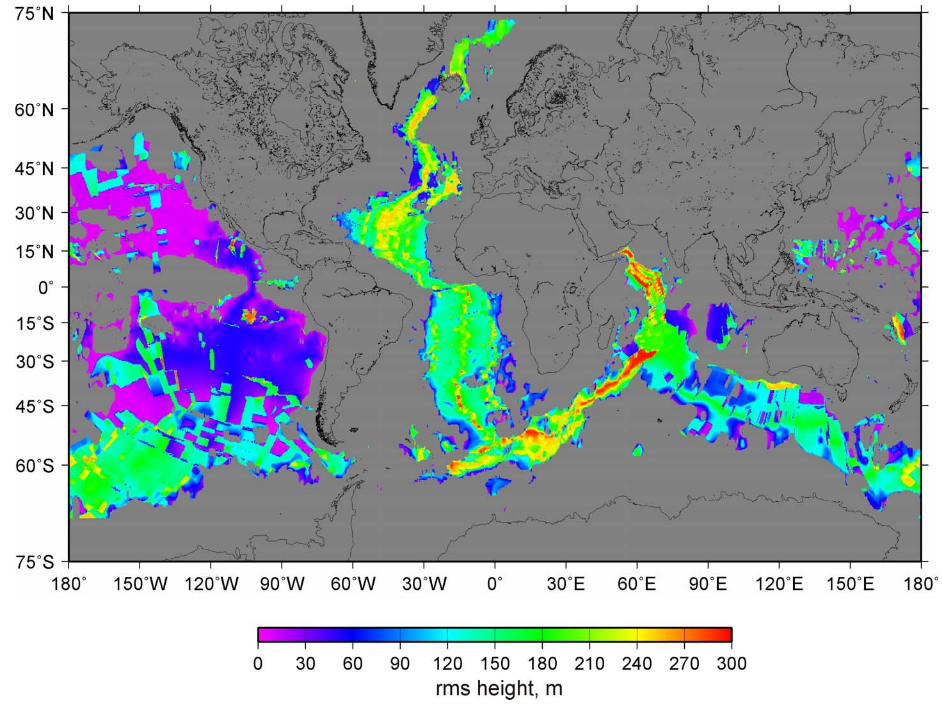

Figure 5. Global prediction of abyssal hill rms heights.

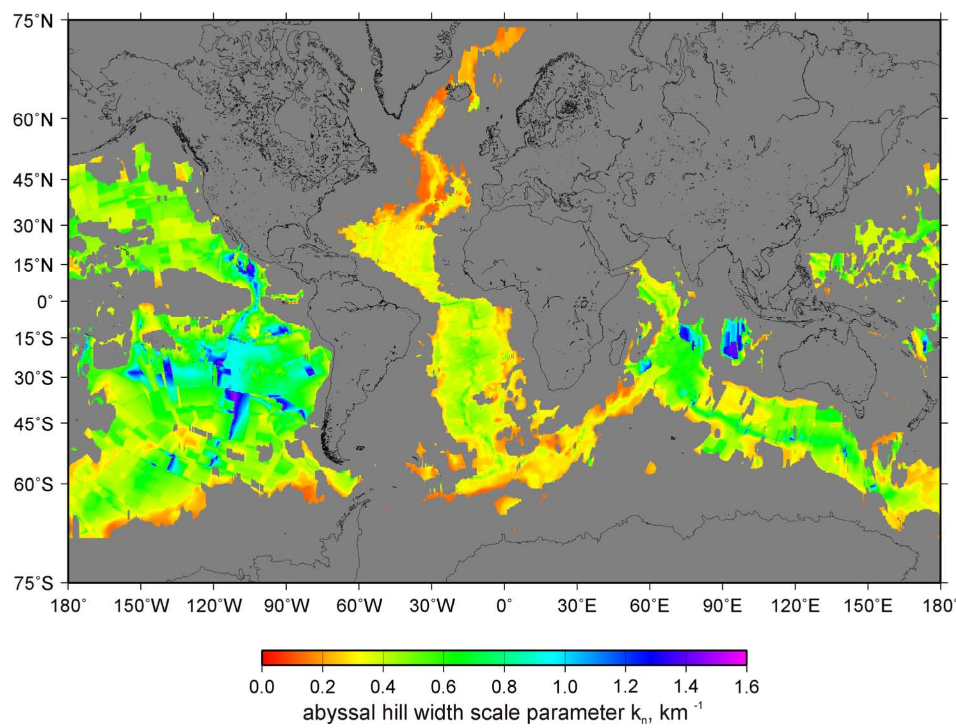

Figure 6. Global prediction of abyssal hill width scale parameter

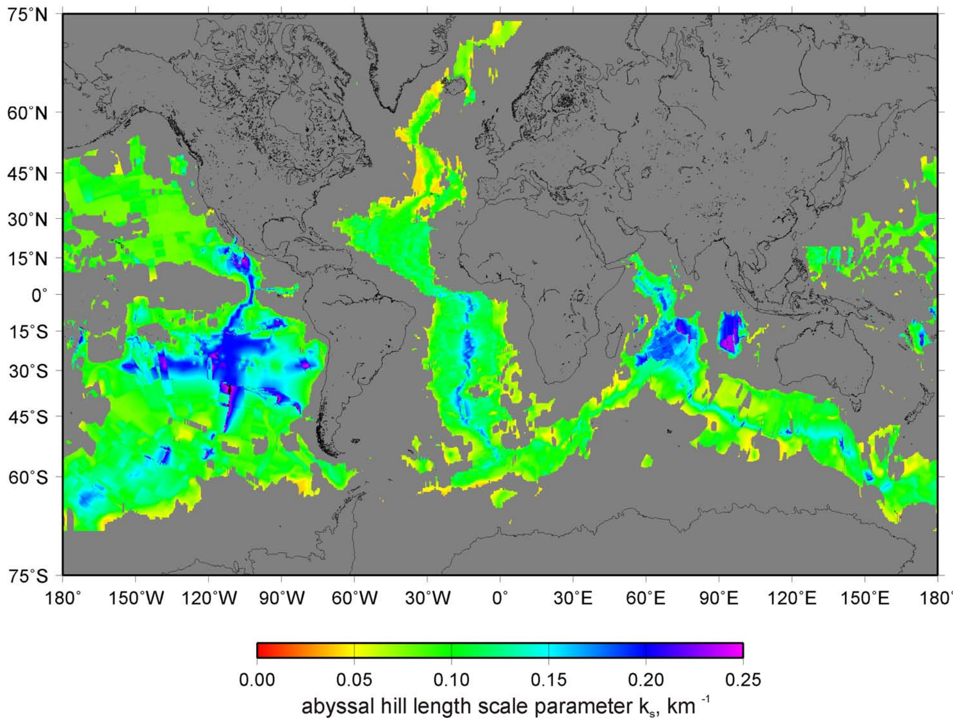

Figure 7. Global prediction of abyssal hill length scale parameter

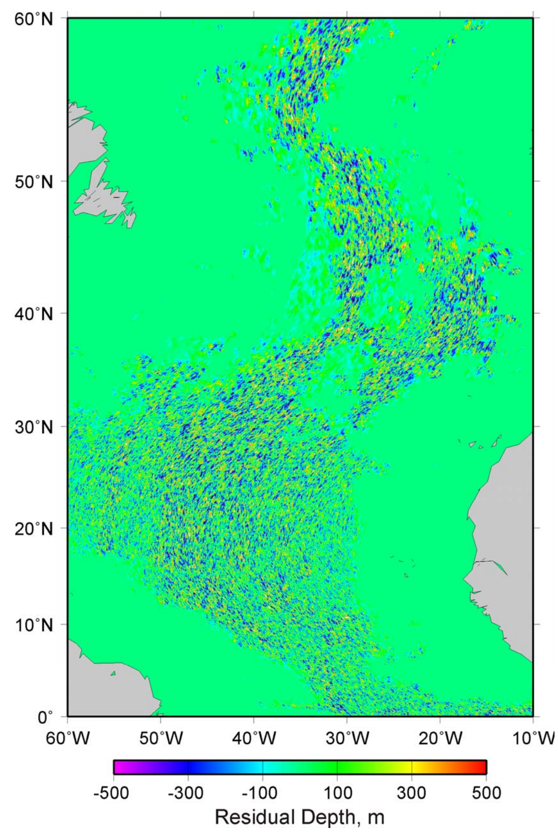

Figure 8. Synthetic abyssal hill roughness for the North Atlantic.

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